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(54) Title: ULTRAHIGH DENSITY LONGITUDINAL RECORDING ON MAGNETIC MEDIA

(57) Abstract: Monitoring the decay of the magnetic domains and refreshing the magnetic domains when the amount of decay has passed an established threshold allows a means to compensate for the superparamagnetic effect and increase the amount of data stored on a recording media. A high frequency reference signal and a low frequency reference signal can be written onto the magnetic media. The low frequency reference signal corresponds to large magnetic bits on the storage media surface, whereas the high frequency reference signal corresponds to small magnetic bits. Because of the large difference in decay rates between the high frequency and low frequency reference signals, any change in the difference of the two signals over time actually reflects the level of signal degradataion that has occurred in the high frequency reference signal. When the difference between the high frequency and low frequency reference signal degradations exceeds a threshold level, the data is refreshed and new high and low frequency reference signals can be written on the magnetic media.

ULTRAHIGH DENSITY LONGITUDINAL RECORDING ON MAGNETIC MEDIA

Related Applications

This application claims priority of United States provisional application Serial Number 60/193,691, filed March 31, 2000.

Field of the Invention

This application relates generally to the field of information storage and more particularly to a method for increasing the reliability of data storage at high areal densities.

Background of the Invention

The need for more efficient data storage devices has become critical with the staggering pace of advances in computer technology. The most common data storage device used today is the disc drive. Most disc drives are composed of one or more magnetic media discs attached to a spindle. A spindle motor rotates the spindle and discs at a constant high speed. An actuator assembly adjacent to the disc(s) has actuator arms extending over the discs, each with one or more flexures extending from each actuator arm. A read/write head is mounted at the distal end of each of the flexures. The read/write head includes an air bearing slider enabling the head to fly in close proximity above the corresponding surface of the associated disc. Information is stored on and retrieved from the magnetic media discs via the read/write head.

Currently, the disc drive industry utilizes longitudinal recording technology. With longitudinal recording, a bit of information is stored by orienting the magnetization direction of each domain on the disc surface lengthwise in the direction of rotation of the disc. A bit may be made up or one or more domains. A domain may consist of one or more magnetic grains, where a grain may consist of one or more atoms. Each disc is divided radially into a finite number of concentric tracks to organize the stored bits. Each track is a certain width and is separated from the adjacent tracks by a "blank space". This blank space prevents information stored in one track from overlapping the information stored in an adjacent track. The number of tracks located on each disc surface is known as the track density.

Each track is subdivided into sections, called segments. Bits are written to and read from these segments by the read/write head. The linear density of bits stored within each segment is called the bit density.

The product of track density and bit density is known as areal density. The recent trend being followed by disc drive manufacturers is to increase the recording media's areal density so that the amount of data stored can be increased without increasing the physical size or the number of discs used in a drive. For example, the areal density of early disc drives was less that 1 Gbits/sq. inch, whereas today, disc drives with areal densities greater than 40 Gbits/sq. inch are being tested. Manufacturers increase areal density by increasing both track density and bit density. Narrowing track width and/or narrowing the width of the blank spaces between tracks increase track density. Bit density is usually increased by increasing the recording speed in order to record higher frequency bits; a higher frequency bit takes up less space on the disc surface.

Packing more information onto a given size magnetic media has certain drawbacks. As mentioned above, the individual magnetic bits located on the recording media become smaller as areal density increases. Furthermore as the frequency of a magnetic bit stored in a magnetic domain increases, the magnetic bit size decreases. However as the frequency of the bit rises, the tendency of the bit orientation to decay, or disorient, increases exponentially, thereby increasing the risk of data loss. (For example, a bit with the frequency of 50.8 MHz may decay over a period of 1000 years; whereas, a bit with only twice that frequency, 101.6 MHz, may decay over a period of 10 years.) At a certain point, magnetic bits become so small that they are unstable at room temperature and spontaneously decay, thereby making data storage impossible. This phenomenon is known as the superparamagnetic effect. Because of the superparamagnetic effect, the amount of data that can physically be stored on a disc surface is limited. It has been predicted that about 100 Gbits/sq. inch is the highest density of data that can be achieved on a magnetic disc using the longitudinal recording method. Furthermore, with the current rate of technological advances, it is predicted that the superparamagnetic limit will be reached within the next two years.

Disc drive manufacturers are investigating non-longitudinal recording techniques such as vertical recording, holographic recording, and special signaling or orientating of the storage media among others in an attempt to overcome the 100 Gbits/sq. inch limit caused by the superparamagnetic effect. However, longitudinal recording offers cost, manufacturing, and technological advantages that the disc drive manufacturers wish to exploit.

Accordingly, there is a need for means or method of exploiting the benefits of longitudinal recording while avoiding or compensating for the superparamagnetic limit.

Summary of the Invention

Against this backdrop the present invention has been developed to increase the amount of data that can reliably be stored on magnetic media. The present invention offers a means to compensate for the superparamagnetic effect and increase the amount of data that can be reliably stored on a recording media by monitoring the decay of the magnetic bits and refreshing the magnetic bits when the amount of decay has passed a pre-established threshold. The present invention can be used for any type of magnetic media storage system such as disc drive and magnetic tape drives among others. However, a disc drive has been used for illustrating the invention.

According to the present invention, a high frequency reference signal and a low frequency reference signal may be either written onto the magnetic media during the disc drive manufacturing process or during normal operation of the drive. The low frequency reference signal corresponds to larger magnetic bits on the storage media surface, whereas the high frequency reference signal corresponds to smaller magnetic bits on the media surface. In the case of a disc drive, these signals can be written to a dedicated system track (called a "super track") or to a dedicated system track sector (called a "super sector"). The reference signals can contain important parametric information such as amplitude, bit error rate, signal to noise ratio, and spectrum information (FFT of the signal).

The low frequency reference signal, because it decays at an exponentially slower rate than the high frequency reference signal, can be used as a baseline to determine the amount of decay in the high frequency signal. Any change in the

difference between the two signals' parametric information actually reflects the level of signal degradation that has occurred in the high frequency reference signal. In other words, the low frequency reference signal's parametric information remains constant (for all practical purposes) when compared to the high frequency reference signal's parametric information. Therefore, if the difference between the two signals' parametric information increases, the increase can be attributed to the high frequency reference signal's decay. Furthermore because the high frequency reference signal corresponds to the higher density and smaller magnetic bit size on the media, any degradation of the high frequency reference signal can be used as an indication of decay in the media's data domains.

When the present invention is applied to a disc drive, the disc drive's read/write head is used to read the high and low frequency reference signals; an average of many read operations is preferably used to determine the difference ("Δ") of the parametric information between the high frequency reference signal and the low frequency reference signal. The difference determined after first writing the signals on the magnetic media ("$\Delta_{original}$") can be recorded on the disk media and/or in system memory as a reference baseline.

Each time the disc drive is subsequently activated, after the signals have first been written on the magnetic media, it can perform a self-diagnostic test. The same real time parametric information, as measured to determine $\Delta_{original}$, is measured and recorded. This real time difference measurement ("Δ_n") is then compared with $\Delta_{original}$. The difference between Δ_n and $\Delta_{original}$ (called "δ") is compared to a predefined threshold limit. If δ exceeds the threshold limit, the user can be warned that a backup and/or refresh procedures should be completed. Storage devices such as CD-ROM's, storage attached network ("SAN"), network attached storage ("NAS"), among others, can be utilized for this back up. Alternatively, the data on the disc can be automatically backed up and/or refreshed without user input. The high frequency and low frequency reference signals can also be refreshed in order to establish a new baseline for the subsequent delta calculation (i.e., a new $\Delta_{original}$).

In accordance with other aspects, the present invention relates to an apparatus for increasing the amount of data reliably stored on magnetic media. The

apparatus includes a controller for writing a high frequency and a low frequency reference signal onto the magnetic media, reading the signals from the magnetic media, determining the difference between the signals, and comparing the difference to a threshold. If the difference exceeds the threshold, the controller notifies the user that the data stored on the magnetic media needs to be refreshed or backed up. Storage devices such as CD-ROM's, storage attached network ("SAN"), network attached storage ("NAS"), among others, can also be utilized for this back up. Alternatively, the apparatus can automatically refresh and/or back up the data stored on the magnetic media without user input.

These and various other features as well as additional advantages which characterize the present invention will be apparent from a reading of the following detailed description and a review of the associated drawings.

Brief Description of the Drawings

FIG. 1 is a plan view of a disc drive incorporating a preferred embodiment of the present invention showing the primary internal components.

FIG. 2 is a graphical representation of the decay rates of a high frequency reference signal, a low frequency reference signal, and data stored in the smallest sized magnetic domain in accordance with a preferred embodiment of the present invention.

FIG. 3 is a graphical representation showing the difference in the decay rates between a high and low frequency reference signal in relationship to a threshold level.

FIG. 4 is a flow chart of the testing method during the manufacturing process in accordance with a preferred embodiment of the present invention.

FIG. 5 is a flow chart of the testing method during normal operation of the disc drive in accordance with a preferred embodiment of the present invention.

FIGS. 6(a)-(c) illustrate preferred embodiments of the present invention for acquiring a number of sample readings for calculating the average magnitudes of the high and low frequency reference signals' parametric information.

Detailed Description

A disc drive **100** constructed in accordance with a preferred embodiment of the present invention is shown in FIG. 1. The disc drive **100** includes a base **102** to which various components of the disc drive **100** are mounted. A top cover **104**, shown partially cut away, cooperates with the base **102** to form an internal, sealed environment for the disc drive in a conventional manner. The components include a spindle motor **106**, which rotates one or more discs **108** at a constant high speed. Information is written to and read from tracks **120** on the discs **108** through the use of an actuator assembly **110**, which rotates during a seek operation about a bearing shaft assembly **112** positioned adjacent the discs **108**. The actuator assembly **110** includes a plurality of actuator arms **114** which extend towards the discs **108**, with one or more flexures **116** extending from each of the actuator arms **114**. Mounted at the distal end of each of the flexures **116** is a transducer head **118**, which includes an air, bearing slider enabling the transducer head **118** to fly in close proximity above the corresponding surface of the associated disc **108**.

During a seek operation, the track **120** position of the transducer heads **118** is controlled through the use of a voice coil motor (VCM) **124**, which typically includes a coil **126** attached to the actuator assembly **110**, as well as one or more permanent magnets **128** which establish a magnetic field in which the coil **126** is immersed. The controlled application of current to the coil **126** causes magnetic interaction between the permanent magnets **128** and the coil **126** so that the coil **126** moves in accordance with the well-known Lorentz relationship. As the coil **126** moves, the actuator assembly **110** pivots about the bearing shaft assembly **112**, and the transducer heads **118** are caused to move over the surfaces of the discs **108**.

The spindle motor **106** is typically de-energized when the disc drive **100** is not in use for extended periods of time. The transducer heads **118** are moved over park zones near the inner diameter of the discs **108** when the drive motor is de-energized. The transducer heads **118** are secured over the park zones through the use of an actuator latch arrangement **122**, which prevents inadvertent rotation of the actuator assembly **110** when the heads are parked.

A flex assembly **130** provides the requisite electrical connection paths for the actuator assembly **110** while allowing pivotal movement of the actuator assembly **110** during operation. The flex assembly **130** includes a preamplifier **132** to which head wires (not shown) are connected; the head wires being routed along the actuator arms **114** and the flexures **116** to the heads **118**. The preamplifier **132** amplifies read signals generated by the heads **118** during a read operation. The flex assembly **130** terminates at a flex bracket **134** for communication through the base deck **102** to a disc drive printed circuit board (not shown) mounted to the bottom side of the disc drive **100**.

The present invention offers a means of increasing the reliability of data stored in tracks **120** on magnetic media discs **108** at high areal densities. More specifically, the present invention compensates for, or counteracts, the superparamagnetic effect. The superparamagnetic effect is a physical phenomenon encountered when the magnetic bits used to store information on magnetic storage devices become extremely small and thermodynamically unstable.

Due to the physical properties of the disc media **108**, the orientation decay rate of a large magnetic bit is exponentially slower than the orientation decay rate of a small magnetic bit. An inverse relationship exists between bit size and bit frequency; as magnetic bit size decreases, magnetic bit frequency increases. It follows that the decay rate of a low frequency magnetic bit on the magnetic media **108** will be exponentially slower than the decay rate of a high frequency magnetic bit on the magnetic media **108**. As a result, a high frequency signal (corresponding to the small, high frequency magnetic bit) and a low frequency signal (corresponding to the large, low frequency magnetic bit) can be written on the magnetic media **108** and monitored as representative of the orientation decay of the magnetic bits.

The low frequency reference signal's decay, for all practical purposes, is negligible when compared to the high frequency reference signal's decay due to the exponential difference in decay rates. Consequently, any change in the difference of the magnitude of the parametric information between the two reference signals actually reflects the level of signal degradation that has occurred in the high frequency reference signal.

In accordance with a preferred embodiment of the present invention, the highest frequency reference signal that can be written on the magnetic media **108** represents and corresponds to the highest frequency, smallest magnetic bits that can be stored on the media **108**. The smallest data bits that can possibly be stored on the magnetic media **108** decay faster than the other data bits, and therefore, can be considered as the worst-case risk for data loss. Any degradation of the high frequency reference signal (after originally being written) can be used as an indication that the smallest magnetic data bits have decayed. The user knows that the smallest magnetic data bits have decayed and recovery and back-up procedures should be instituted in order to prevent data loss once the high frequency reference signal's decay surpasses a threshold value.

It is obvious that a frequency can be chosen for the "high frequency" reference signal that does not directly correspond to the smallest possible magnetic bit size. A lower, "high frequency" reference signal may be selected, depending on how much time the manufacturer or user wishes to be fore-warned that data has decayed. However, in a preferred embodiment, the "high frequency" is chosen to correspond to the smallest data bit stored on the magnetic media. The preferred embodiment affords the greatest amount of forewarning of data decay because the frequency that corresponds to the smallest data bit stored on the magnetic media **108** is chosen.

According to the present invention, a high frequency reference signal and a low frequency reference signal are written onto the magnetic media **108** during the manufacturing process and/or during normal operation. The low frequency reference signal corresponds to larger magnetic bits on the storage media surface, whereas the high frequency reference signal corresponds to smallest magnetic bits on the media surface.

FIG. 2 is a plot of percent bit orientation decay versus time that illustrates the decay rates of a low frequency (6T) reference signal **201** on the horizontal axis, a highest frequency (1T) reference signal **202** that can be written by the particular disc drive system, and the smallest magnetic domain data bit **203** that can be stored on the particular magnetic media **108**. It should be noted that the period (designated "T"), equals 1/f, where "f" is the highest frequency that can be written

by the particular disc drive system being used. It should further be noted that the low frequency signal should be at least a factor of 2, or 2T, the period of the highest frequency signal. In a preferred embodiment, a 6T signal is used and, as shown in FIG. 2, is drawn coincident with the time axis because the 6T frequency reference signal's decay rate is essentially negligible when compared with the decay rate of the 1T frequency signal. As can be seen in FIG. 2, the high frequency reference signal's decay rate **202** is comparable to the smallest magnetic data bit's decay rate **203** (the curves are offset in time because the high frequency reference signal is usually written on the super track or in the super sector by the manufacturer before the user data is written). Therefore, the high frequency reference signal's decay **202** can be used as an indicator of the amount of decay that has occurred in the smallest magnetic data bit **203**. This is important because the smallest magnetic bit **203**, due to the superparamagnetic effect, will decay at a faster rate than a larger magnetic bit. The decay of the smallest data bit **203** is, in other words, the worst-case scenario of decay for all magnetic data bits in the entire data storage region on the magnetic media **108**.

FIG. 2 also illustrates that the decay rate of the high frequency reference signal **202** is exponentially larger than the decay rate of the low frequency reference signal **201**; and therefore, the low frequency reference signal's decay rate **201** can be used as a baseline for determining the change in the high frequency reference signal's **202** (and therefore, the smallest magnetic data bit's **203**) decay rate. The difference between the high frequency reference signal's decay rate **202** and the low frequency reference signal's decay rate **201** can be used to determine when data needs to be refreshed.

FIG. 3 is a plot that illustrates signal decay versus time. The area under the curve represents the difference, Δ, between the high frequency reference signal's (1T) decay rate **202** and the low reference signal's (6T) decay rate **201**. It should be noted that the low frequency signal should be at least a factor of 2, or 2T, the period of the highest frequency signal. In a preferred embodiment, a 6T signal **201** is used as a baseline because of its slow decay rate as compared to the 1T signal **202**. The difference between the decay rates of the 1T signal **202** and 6T signal **201** actually represents the decay of the 1T signal **202** (because the 6T signal **201**,

for all practical purposes, remains constants over time), and similarly, corresponds to the decay of the smallest magnetic data bit **203** (i.e., worst-case scenario for the whole data region). Area **304** under the curve **202** and to the left of the threshold value **303** in FIG. 3 represents data that is acceptably safe. Any data that falls within Area **304** does not need to be refreshed. Area **305** under the curve **202** and to the right of the threshold value **303** in FIG. 3 represents data that has decayed past an unacceptable amount and should be refreshed.

A disc drive **100** is used here to illustrate a preferred embodiment, although the present invention pertains to other magnetic media storage devices such as tape drives among others. FIG. 4 shows the preferred operational steps of the method **400** in accordance with the invention as implemented during the drive **100** manufacturing process. The high and low frequency reference signals **201, 202** are first written to a system track (in the "super track" **601** or "super sector" **602**) on a disc **108** in operation **401**. The reference signals **201, 202** can contain important parametric information such as amplitude, bit error rate, signal to noise ratio, and spectrum information (FFT of the signal). Operational control is then passed to operation **402**.

In operation **402**, the disc drive's read/write head **118** is used to read the reference signals **201, 202** from the system track. It is preferable that operation **402** acquires many samples of the high and low frequency reference signals **201, 202**.

Control passes to operation **403** once a sufficient number of samples are acquired by operation **402**. Operation **403** determines the average magnitude of the parametric information of each reference signal **201, 202**. Operation **403** can be implemented using the channel chip located on the disc drive **100** or by another processor on or off of the disc drive **100**. The average magnitude values calculated by operation **403** are then passed to operation **404**.

Operation **404** determines the difference ("Δ") between average value of the high frequency reference signal **202** and the average value of the low frequency reference signal **201** passed from operation **403**. Operation **404** can be implemented using the channel chip located on the external servo control printed circuit board on disc drive **100** or by another processor on or off of disc drive **100**.

The difference (i.e., Δ) is a figure of merit between the high and low frequency reference signals **201, 202**. In effect, the Δ is a common mode noise rejection value. This common mode rejection value can then be used to eliminate "noises" (such as media common noise, head electrical noise, head electrical signal imperfections, and preamplifier noise among others) from the readings of both the high and low frequency reference signals. This common mode rejection value can also be used to eliminate environmental factors such as temperature, atmospheric pressure, and humidity among others.

The Δ value obtained the first time operation **404** is completed after writing the reference signals **201, 202** on the media (designated as "$\Delta_{original}$") is saved in a log as a reference baseline by operation **405**. For a disc drive **100**, operation **405** stores $\Delta_{original}$ in a log on the disc media **108** (preferably in the disc's super sector **602** or super track **601**) or in system memory for future use when disc drive **100** is operated. (Note that other information such as the parametric data and the warning threshold limit value can also be stored with $\Delta_{original}$.) Operational control then transfers to operation **406**.

Operation **406** exercises control after $\Delta_{original}$ is stored by operation **405**. Operation **406** either prompts the manufacturer/user for a threshold limit input **303**, or it retrieves a threshold limit **303** previously stored by the manufacturer/user on the disc media **108**, in system memory, or somewhere accessible by the disc drive **100** unit. Operation **406** compares $\Delta_{original}$ to the threshold limit **303** once the values for the threshold limit **303** and $\Delta_{original}$ are obtained.

Comparison of $\Delta_{original}$ to the threshold value **303** leads to determination operation **407**. If $\Delta_{original}$ exceeds the threshold value **303**, control branches "YES" and disc drive **100** fails. Operation **408** assumes control if disc drive **100** fails. Disc drive **100** is rejected in operation **408**. If $\Delta_{original}$ does not exceed the threshold value **303**, control branches "NO" and disc drive **100** passes. (Note: the evaluation completed by the present invention can be combined with existing disc drive certification processes as one of many steps for determining whether a disc drive **100** passes or fails.) Operation **409** assumes control if disc drive **100** passes and it

is either installed in a computer system or shipped directly to a customer (not shown).

Again, a disc drive **100** is used to illustrate a preferred embodiment even though the present invention pertains to all magnetic media storage devices such as tape drives among others. FIG. 5 shows the preferred operational process **500** of the invention as implemented during a normal disc drive **100** start-up operation. Process **500** is normally implemented after process **400** has already been applied during the manufacturing process. Process **500** begins when a computer system using a disc drive **100** is turned on or rebooted. The self-diagnostic test of operation **501** can occur each time that the computer system activates the disc drive **100**. Operation **501** can be controlled by disc drive system firmware or in the operating system software. Operation **501** may also include any number of other user or manufacturer-specified diagnostic steps to determine whether disc drive **100** is functioning properly or whether some remedial action needs to be undertaken.

Once self-test operation **501** is implemented, operation **502** engages. Operation **502** uses the disc drive read/write head **118** to read the reference signals **201, 202** stored on the disc media **108** during disc drive **100** manufacturing. Operation **502** measures the real time parametric information of the high and low frequency reference signals **201, 202**. Note: this is the same parametric information that was measured in operation **402** during the manufacturing process (i.e., the information used to determine $\Delta_{original}$). It is preferable that operation **502** acquires many samples of the high and low frequency reference signals **201, 202**. Once a sufficient number of samples are acquired, control passes to operation **503**.

Operation **503**, determines the average magnitude of the parametric information for both the high frequency and low frequency reference signals **201, 202**. Operation **503** can be implemented using the channel chip located on the external servo control printed circuit board on disc drive **100** or by another processor on or off of the disc drive **100**. The average values calculated by operation **503** are then passed to operation **504**.

Operation **504** determines the difference ("Δ_n", where n is the number of times the self-test has been run) between the average parametric magnitude value of the high frequency reference signal **202** and the average parametric magnitude value of the low frequency reference signal **201** passed from operation **503**. Operation **504** can be implemented using the channel chip located on the external servo control printed circuit board on disc drive **100** or by another processor on or off of the disc drive **100**. The difference (i.e., Δ_n) is a figure of merit between the parametric magnitudes of the high and low frequency reference signals **201, 202**. Δ_n is, in effect, a common mode noise rejection value. This common mode rejection value can be used to eliminate "noises" (such as media common noise, head electrical noise, head electrical signal imperfections, and preamplifier noise among others) from the readings of both the high and low frequency reference signals **201, 202**. This common mode rejection value can also be used to eliminate environmental factors such as temperature, atmospheric pressure, and humidity among others.

Operation **505** takes the value Δ_n, obtained by operation **504**, and stores it in a log on the system. For a disc drive **100**, Operation **505** stores Δ_n in a log on the disk media **108** (preferably in the disc's super sector **602** or super track **601**) or in system memory (Note that other information such as the parametric data, warning threshold limit value **303**, and $\Delta_{original}$ can also be stored with Δ_n). Every value stored can be used for later diagnostic test. A manufacturer, for example, can use the stored information to determine the rate of data failure for a certain model of disc drive, to control trending to optimize the threshold settings **303**, and thereafter, to implement steps to improve disc drive performance and yield.

Operation **506** exercises control after Δ_n is stored by operation **505**. Operation **506** accepts Δ_n from operation **505** and also retrieves the value of $\Delta_{original}$ previously stored on the disc media **108** or in system memory by operation **405**. Operation **506** determines the difference ("δ") between Δ_n and $\Delta_{original}$. The difference, δ, between Δ_n and $\Delta_{original}$ represents the amount of data decay that has occurred on the disc drive **100** since the high and low frequency reference signals **201, 202** were first written or refreshed. The difference (i.e., δ) can be considered

as a figure of merit between $\Delta_{original}$ and Δ_n. δ is, in effect, a common mode noise rejection value for $\Delta_{original}$ and Δ_n.

Operation **507** accepts δ, the value of the difference between Δ_n and $\Delta_{original}$ as determined in operation **506**, and either prompts the user to enter a threshold value, $\delta_{threshold}$, or retrieves the threshold value, $\delta_{threshold}$, previously stored by the manufacturer on the disc media **108** or in system memory. Operation **507** then compares δ, obtained in operation **506**, to the threshold value, $\delta_{threshold}$.

Control then passes to determination operation **508**. If δ, the difference between Δ_n and $\Delta_{original}$, does not exceed $\delta_{threshold}$, control branches "NO" and operation **509** assumes control. Operation **509** notifies the user that the data is safe and that a backup or refresh procedure need to be implemented. After operation **509**, the remaining steps (not shown) of the disc drive **100** self-test are completed and normal disc drive **100** operation begins.

Conversely, if δ, the difference between Δ_n and $\Delta_{original}$, exceeds $\delta_{threshold}$ in determination operation **508**, control branches "YES" and operation **510** assumes control. Operation **510** automatically refreshes the high frequency and low frequency reference signals **201, 202** (i.e., writes a new high frequency **202** and a new low frequency **201** reference signal on the disc media **108**) and backs-up and/or refreshes (i.e., re-writes) the data on the disc media **108**. Operation **510** can alternatively be set to prompt the user that a backup and/or refresh procedure needs to be implemented. Refreshing the high frequency and low frequency reference signals **201, 202** eliminates the signal degradation that has occurred since the time the product was shipped from the manufacturer. In other words, the high frequency and low frequency reference signals **201, 202** are refreshed with the data in order to maintain the close correspondence between the high frequency signal's decay **202** and the orientation decay of the data bits. The link between the high frequency reference signal **202** and the data bit's orientation would be broken and data would either be rewritten too often or not rewritten when the need existed if the high frequency reference signal **202** was not refreshed. Control passes to operation **511** after operation **510** is completed.

Operation **511** determines a new $\Delta_{original}$ value. Operation **511** entails the same steps as completed in steps **402, 403,** and **404.** In short, operation **511** entails: 1) using the disc drive read/write head **118** to read the new reference signals (preferably acquiring many samples of the high and low frequency reference signals **201, 202**); 2) determining the average magnitude of the parametric information for each reference signal **201, 202**; and 3) determining the difference ($\Delta_{original}$) between the average magnitude values of the new high frequency reference signal **202** and the new low frequency reference signal **201**. A new $\Delta_{original}$ value is determined because the reference signals **201, 202** and data were refreshed in operation **510.**

After operation **511** is complete and a new $\Delta_{original}$ had been determined, operation **512** assumes control. Operation **512** saves the new $\Delta_{original}$ to the log on the disc media **108** (preferably in the disc's super sector) or in system memory. The new $\Delta_{original}$ can overwrite the old $\Delta_{original}$, or alternatively, the old $\Delta_{original}$ can be maintained in the log. As previously mentioned, the values stored in the log (Δ_{n}, $_{n-1}$, ... $\Delta_{original}$, etc.) can be used as a diagnostic tool to determine the health of the disk drive **100**, as an indicator of whether the disc drive **100** should be replaced, and as a means to optimize the value for $\delta_{threshold}$ among others. Operational process **500** terminates after operation **512** is completed. Alternatively after operation **512** is completed, operational process **500** can be restarted (not shown) to insure that the data was effectively refreshed.

FIG. 6(a) illustrates a preferred embodiment for obtaining multiple readings of the high and low frequency reference signals **201, 202** as completed by operation **402** and operation **502.** The reference signals **201, 202** are stored in multiple super sectors **602** located in a dedicated super track **601** on the disc surface (such as disc **108** shown in FIG. 1). A super track **601** is a track **120** on disc **108** that only contains super sectors **602.** In this embodiment, one complete disc **108** revolution with the read head **118** reading the super track **601** can obtain a sufficient number of samples for the averaging calculation. Additionally, a partial revolution with the read head **118** reading a predetermined number of super sectors **602** on the super track **601** may also obtain a sufficient number of samples for the averaging

calculation. The length of the partial revolution (i.e., the number of super sectors **602** read) can be predetermined to acquire a desired number of samples sufficient for the averaging calculation.

FIG. 6(b) illustrates another embodiment for obtaining multiple readings of the high and low frequency reference signals as completed by operation **402** and operation **502** in which the reference signals are stored in a single super sector **602** located on a system track **603** on the disc surface (such as disc **108** shown in FIG. 1). A system track **603** is a track **120** on disc **108** that contains a super sector **602.** A number of revolutions with the read head reading the super sector **602** must be completed to obtain a sufficient number of samples for averaging. The number of revolutions can be predetermined to acquire a desired number of samples sufficient for the averaging calculation.

FIG. 6(c) illustrates another embodiment for obtaining multiple readings of the high and low frequency reference signals **201, 202** as completed by operation **402** and operation **502** in which the reference signals **201, 202** are stored in multiple super sectors **602** located on a system track **603** on the disc surface (such as disc **108** shown in FIG. 1). A system track **603** is a track **120** on disc **108** that contains a super sector **602.** The number of super sectors **602** located on system track **603** can correspond to the number of samples that are desired to complete the averaging calculation, thereby reducing the amount of time that the read head **118** spends reading the system track **603.** Furthermore, the super sectors **602** can be contiguous with one another about system track **603,** placed randomly about system track **603** or placed in some pattern around system track **603.**

It will be clear that the present invention is well adapted to attain the ends and advantages mentioned as well as those inherent therein. While a presently preferred embodiment has been described above for purposes of this disclosure, various changes and modifications may be made which are well within the scope of the present invention. For example, the super sector **602,** or super track **601,** containing the high frequency reference signal **202** and the low frequency reference signal **201** are located at the inner diameter of disc **108.** In this case when the high frequency reference signal **202** (and consequently the data bit orientation **203**) decays past the threshold limit **303,** all data on the disc **108** can be refreshed.

The super sector **602**, or super track **601**, containing the high frequency reference signal **202** and the low frequency reference signal **201** can alternatively be located at the outer diameter of disc **108**. In this case, when the high frequency reference signal **202** (and consequently the data domain orientation **203**) decays past the threshold limit **303**, all data on the disc **108** can be refreshed.

The super sector **602**, or super track **601**, containing the high frequency reference signal **202** and the low frequency reference signal **201** can also be located at the middle diameter of disc **108**. In this case when the high frequency reference signal **202** (and consequently the data domain orientation **203**) decays past the threshold limit **303**, all the data on the disc **108** can be refreshed.

Multiple super sectors **602**, or super tracks **601**, can be located in different radial regions of the recording media **108** in order to create "data zones". In this case, each super sector **602**, or super track **601**, may have the same or different high and low frequency reference signals **201, 202**, and may have the same or different threshold values **303**, saved within its respective super sector **602** or super track **601**. It is preferable, however, to designate different threshold values **303** for each data zone depending on the radial location of the super sector **602** or super track **601**. Preferably, the threshold value **303** is increased as the super sector's **602** or super track's **601** radial location approaches the outer diameter ("OD") of disc **108**. A higher threshold value **303** compensates for a larger Δ that occurs as the super sector's **602**, or super track's **601**, radial location approaches the OD. A larger Δ results because the disc data rate increases as the disc's **108** OD is approached and because higher mechanical non-repeatable-run-out ("NRRO") occurs as the disc's **108** OD is approached. The measurement of data degradation within each data zone would be monitored using the super sector **602** or super track **601** corresponding to that zone. In this alternative only the data zone with data degradation exceeding that specific zone's threshold value **303** is refreshed. Because only the portion of the disc **108** with "unsafe" data is refreshed, the time needed for backup and refresh procedures is reduced and system resources are conserved. One example is a disc **108** divided into three data zones, each data zone controlled by a separate super sector **602** or super track **601**, which has a distinct

high frequency reference signal **202**, low frequency reference signal **201** and threshold value **303**. A separate Δ (Δ_{zone1}, Δ_{zone2}, and Δ_{zone3}) will be determined for each zone. If Δ_{zone3} exceeds the threshold **303** for zone three, only data located in zone three will be refreshed.

In yet another embodiment of this invention, each track **120** can contain a high frequency reference signal **202** and a low frequency reference signal **201** so that the data quality can be determined on a track-by-track basis. Only those tracks **120** with data degradation exceeding the threshold value **303** will be refreshed; thereby reducing backup and refresh time and conserving system resources.

In summary, the present invention may be viewed as a method (such as shown in operational flow process **400**) of increasing the amount of data that can be reliably stored on a magnetic media (such as **108**). The method includes writing a high frequency reference signal (such as **202**) and a low frequency reference signal (such as **201**) on the magnetic media (such as **108**), wherein the high frequency reference signal (such as **202**) corresponds to a small magnetic data bit on the magnetic media (such as **108**) and the low frequency reference signal (such as **201**) corresponds to a large magnetic data bit on the magnetic media (such as **108**) (such as shown in Fig. 2). Next the high frequency (such as **202**) and the low frequency (such as **201**) reference signals are read from the magnetic media (such as **108**) and the difference (such as Δ) between the high frequency (such as **202**) and the low frequency (such as **201**) reference signals is determined. The difference (such as Δ) between the high frequency (such as **202**) and the low frequency (such as **201**) reference signals is compared to a threshold level (such as **303**) and the data stored on the magnetic media (such as **108**) is refreshed if the difference (such as Δ) between the high frequency (such as **202**) and the low frequency (such as **201**) reference signals exceeds the threshold level (such as **303**)(such as shown in Fig. 3).

The high frequency reference signal (such as **202**) and the low frequency reference signal (such as **201**) can include information such as amplitude, bit error rate, signal to noise ratio, and spectrum information. Furthermore, the magnetic media (such as **108**) has system tracks (such as **601, 603**). Each system track (such

as **601**, **603**) having a super sector (such as **602**) located on the system track (such as **601**, **603**) containing the stored high frequency (such as **202**) and the low frequency (such as **201**) reference signals (such as shown in Figs. 6(a) - 6(c)).

Additionally, the reading step of the described method can be viewed as taking multiple readings of the high frequency reference signal (such as **202**) and of the low frequency reference signal (such as **201**) in a predetermined number of super sectors (such as **602**). An average value for each of the high frequency reference signals (such as **202**) for each of the low frequency reference signals (such as **201**) is determined, and the average values are used in the described method to determine the difference (such as Δ) between the high frequency reference signal (such as **202**) and the low frequency reference signal (such as **201**).

Furthermore, the reading step of the described method can be viewed as taking multiple readings of the high frequency reference signal (such as **202**) and of the low frequency reference signal (such as **201**) by reading a single super sector (such as **602**) a predetermined number of times. An average value for each of the high frequency reference signals (such as 202) and each of the low frequency reference signals (such as **201**) is determined, and the average values are used in the described method to determine the difference (such as Δ) between the high frequency reference signal (such as **202**) and the low frequency reference signal (such as **201**).

Finally, the high frequency reference signal (such as **202**) in the described method represents the highest frequency that can be written on the magnetic media (such as **108**). The highest frequency corresponds to the smallest magnetic data bit (such as **203**) that can be written on the magnetic media (such as shown in Fig. 2). Furthermore, the period of the low frequency reference signal (such as **201**) is at least two times the period of the high frequency reference signal (such as **202**) so that the low frequency reference signal's (such as **201**) decay rate appears to be zero when compared to the high frequency reference signal's (such as **202**) decay rate (such as shown in Figs. 2 and 3).

Alternatively, the present invention may be viewed as a method (such as shown in operational flow process **400** and **500**) for increasing the amount of data

that can be reliably stored on a magnetic media (such as **108**), wherein the media has a number of system tracks (such as **601, 603**) each system track (such as **601, 603**) having a super sector (such as **602**). The invention can be implemented by dividing the magnetic media (such as **108**) into radial data zones, each data zone having a corresponding system track (such as **601, 603**) and a corresponding threshold level (such as **303**). A high frequency reference signal (such as **202**) (corresponding to a small magnetic data bit) and a low frequency reference signal (such as **201**) (corresponding to a large magnetic data bit) (such as shown in Figs. 2 and 3) can be written to each super sector (such as **602**) in each data zone. The high frequency (such as **202**) and the low frequency (such as **201**) reference signals from each data zone's system track's super sector (such as **602**) is read and the difference (such as Δ) between the high frequency (such as **202**) and the low frequency (such as **201**) reference signals for each data zone is determined. The difference (such as Δ) between the high frequency (such as **202**) and the low frequency (such as **201**) reference signals for each data zone is compared to the threshold level (such as **303**) for each data zone, and the data stored within one of the data zones is refreshed if the difference (such as Δ) between the high frequency (such as **202**) and low frequency (such as **201**) reference signals for that one data zone exceeds the threshold level (such as **303**) for that one data zone.

The high frequency reference signal (such as **202**) in a specific data zone can represent the highest frequency that can be written on the magnetic media (such as **108**) in that specific data zone. The highest frequency reference signal (such as **202**) corresponds to the smallest magnetic data bit (such as **203**) that can be written on the magnetic media (such as **108**) in that specific data zone (such as shown in Fig. 2). Furthermore, the period of the low frequency reference signal (such as **201**) in that specific data zone is at least two times the period of the high frequency reference signal (such as **202**) in that specific data zone so that the low frequency reference signal's (such as **201**) decay rate appears to be zero when compared to the high frequency reference signal's (such as **202**) decay rate (such as shown in Figs. 2 and 3). The high frequency reference signals (such as **202**) and the low frequency reference signals (such as **201**) stored in each data zone can

include information such as amplitude, bit error rate, signal to noise ratio, and spectrum information.

Additionally, the reading step of the described alternative method can be viewed as taking multiple readings of the high frequency reference signals (such as **202**) and of the low frequency reference signals (such as **201**) in each data zone by reading a predetermined number of super sectors (such as **602**). The average values for the high frequency reference signals (such as **202**) and the low frequency reference signals (such as **201**) are determined, and the difference (such as Δ) between the high frequency reference signals (such as **202**) and the low frequency reference signals (such as **201**) for each data zone is determined using the average values.

Furthermore, the reading step of the described alternative method can be viewed as taking multiple readings of the high frequency reference signals (such as **202**) and of the low frequency reference signals (such as **201**) in each data zone by reading a single super sector (such as **602**) in each data zone a predetermined number of times. The average values for the high frequency reference signals (such as **202**) and the low frequency reference signals (such as **201**) are determined, and the difference (such as Δ) between the high frequency reference signals (such as **202**) and the low frequency reference signals (such as **201**) for each data zone is determined using the average values.

Finally, the value of the threshold level (such as **303**) for the described alternative method can be viewed as changing according to the radial location of the system track (such as **601, 603**) containing the super sector (such as **602**).

The present invention may also be viewed as a method (such as shown in operational flow process **500**) for increasing the amount of data that can be stored on a magnetic media (such as **108**). The second alternative method includes writing a high frequency reference signal (such as **202**) and a low frequency reference signal (such as **201**) on the magnetic media (such as **108**), wherein the high frequency reference signal (such as **202**) corresponds to a small magnetic data bit on the magnetic media, and the low frequency reference signal (such as **201**) corresponds to a large magnetic data bit on the magnetic media (such as shown in Fig. 2). Next, a first high frequency reference signal (such as **202**) reading and a

first low frequency reference signal (such as **201**) reading are taken from the magnetic media (such as **108**). The difference (such as $\Delta_{original}$) between the first high frequency reference signal (such as **202**) and the first low frequency reference signal (such as **201**) readings is determined and a first value corresponding to the difference (such as $\Delta_{original}$) between the first high frequency reference signal (such as **202**) reading and the first low frequency reference signal (such as **201**) reading is recorded.

A second high frequency reference signal (such as **202**) reading and a second low frequency reference signal (such as **201**) reading are taken from the magnetic media (such as **108**) after the difference (such as $\Delta_{original}$) between the first high and first low frequency reference signals (such as **201** and **202**) are recorded. The difference (such as Δ_n) between the second high frequency reference signal (such as **202**) reading and the second low frequency reference signal (such as **201**) reading is determined and a second value corresponding to the difference (such as Δ_n) between the second high frequency reference signal (such as **202**) reading and the second low frequency reference signal (such as **201**) reading is recorded. The difference (such as δ) between the first recorded value and the second recorded value is determined. The data on the magnetic media (such as **108**) is refreshed if the difference (such as δ) between the first recorded value and the second recorded value exceeds a threshold level (such as **303**).

Additionally, the steps of writing, reading, determining the difference (such as $\Delta_{original}$), and storing the difference value pertaining to the first high frequency reference signal (such as **202**) and the first low frequency reference signal (such as **201**) in the described second alternative method can be viewed as being performed during the data storage device (such as **108**) manufacturing process. Furthermore, the difference (such as $\Delta_{original}$) can be compared to a threshold (such as **304**) during the data storage device (such as **100**) manufacturing process as part of the data storage device (such as **100**) certification process.

The first and second high frequency signals (such as **202**) and the first and second low frequency signals (such as **201**) in the described second alternative

method can include amplitude, bit error rate, signal to noise ratio, and spectrum information.

Additionally, the reading steps in the described second alternative method can be viewed as taking multiple readings of the first high frequency reference signal (such as **202**), the second high frequency reference signal (such as **202**), the first low frequency reference signal (such as **201**), and the second low frequency reference signal (such as **201**). The average value for each signal is determined, and the difference (such as $\Delta_{original}$) between the first high (such as **202**) and low (such as **201**) frequency reference signals and the difference (such as Δ_n) between second high (such as **202**) and low (such as **201**) frequency reference signals is determined using the average values.

Finally, the high frequency reference signal (such as **202**) described second alternative method represents the highest frequency that can be written on the magnetic media (such as **108**). The highest frequency reference signal (such as **202**) corresponds to the smallest magnetic data bit (such as **203**) that can be written on the magnetic media (such as **108**)(such as shown in Fig. 2). Furthermore, the period of the low frequency reference signal (such as **201**) has a period at least two times the period of the high frequency reference signal (such as **202**) so that the low frequency reference signal's (such as **201**) decay rate appears to be zero when compared to the high frequency reference signal's (such as **202**) decay rate (such as shown in Figs. 2 and 3).

The present invention may further be viewed as an apparatus for increasing the amount of data that can be stored on a magnetic media (such as **108**). The apparatus has a high frequency signal generator and a low frequency signal generator. The apparatus has a write element to write the high frequency reference signal (such as **202**) and the low frequency reference signal (such as **201**) to the magnetic media (such as **108**), and a read element to read the high frequency reference signal (such as **202**) and the low frequency signal (such as **201**) from the magnetic media (such as **108**). The apparatus also has an electrical circuit to determine a difference (such as Δ) between the high frequency reference signal (such as **202**) and low frequency reference signal (such as **201**), an electrical circuit

to compare the difference (such as Δ) between the high frequency reference signal (such as **202**) and the low frequency reference signal (such as **201**) to a threshold value (such as **303**), and a controller that activates the write element to refresh the data stored on the magnetic media (such as **108**) if the difference (such as Δ) between the high frequency reference signal (such as **202**) and low frequency reference signal (such as **201**) is greater than the threshold value (such as **303**).

Numerous other changes may be made which will readily suggest themselves to those skilled in the art and which are encompassed in the spirit of the invention disclosed and as defined in the appended claims.

Claims

What is claimed is:

1. A method for increasing the amount of data that can be reliably stored on a magnetic media comprising steps of:

(a) writing a high frequency reference signal and a low frequency reference signal on the magnetic media, wherein the high frequency reference signal corresponds to a small magnetic data bit on the magnetic media and the low frequency reference signal corresponds to a large magnetic data bit on the magnetic media;

(b) reading the high frequency and the low frequency reference signals;

(c) determining a difference between the high frequency and the low frequency reference signals;

(d) comparing the difference between the high frequency and the low frequency reference signals to a threshold level; and

(e) refreshing data stored on the magnetic media if the difference between the high frequency and the low frequency reference signals exceeds the threshold level.

2. The method of claim 1, wherein the high frequency reference signal and the low frequency reference signal in writing step (a) include amplitude, bit error rate, signal to noise ratio, and spectrum information.

3. The method of claim 1, wherein the magnetic media has system tracks, each system track having a super sector located on the system track containing the stored high frequency and the low frequency reference signals.

4. The method of claim 3, wherein the reading step (b) comprises:

(b)(i) taking multiple readings of the high frequency reference signal and of the low frequency reference signal in a

predetermined number of super sectors, the super sectors located on a system track;

(b)(ii) determining an average value for each of the high frequency reference signals and each of the low frequency reference signals; and,

(b)(iii) using the average values in determining step (c) to determine the difference between the high frequency reference signal and the low frequency reference signal.

5. The method of claim 3, wherein the reading step (b) comprises:

(b)(i) taking multiple readings of the high frequency reference signal and of the low frequency reference signal by reading a single super sector a predetermined number of times;

(b)(ii) determining an average value for each of the high frequency reference signals and each of the low frequency reference signals; and,

(b)(iii) using the average values in determining step (c) to determine the difference between the high frequency reference signal and the low frequency reference signal.

6. The method of claim 1, wherein the high frequency reference signal represents the highest frequency that can be written on the magnetic media and corresponds to the smallest magnetic data bit that can be written on the magnetic media and the period of the low frequency reference signal is at least two times the period of the high frequency reference signal.

7. A method for increasing the amount of data that can be reliably stored on a magnetic media, wherein the media has a number of system tracks, each system track having a super sector, the method comprising steps of:

(a) dividing the magnetic media into radial data zones, each data zone having a corresponding system track and a corresponding threshold level;

(b) writing a high frequency reference signal and a low frequency reference signal to each super sector in each data zone, wherein the high frequency reference signal corresponds to a small magnetic data bit on the magnetic media, and the low frequency reference signal corresponds to a large magnetic data bit on the magnetic media;

(c) reading the high frequency and the low frequency reference signals from each data zone's system track's super sector;

(d) determining a difference between the high frequency and the low frequency reference signals for each data zone;

(e) comparing the difference between the high frequency and the low frequency reference signals for each data zone to the threshold level for each data zone; and

(f) refreshing the data stored within one of the data zones if the difference between the high frequency and low frequency reference signals for that one data zone exceeds the threshold level for that one data zone.

8. The method of claim 7, wherein the high frequency reference signal in a specific data zone represents the highest frequency that can be written on the magnetic media in that specific data zone and corresponds to the smallest magnetic data bit that can be written on the magnetic media in that specific data zone and the low frequency reference signal has a period at least two times the period of the high frequency reference signal in that specific data zone.

9. The method of claim 7, wherein writing step (b) includes writing amplitude, bit error rate, signal to noise ratio, and spectrum information to each super sector.

10. The method of claim 7, wherein the reading step (c) comprises:

(c)(i) taking multiple readings of the high frequency reference signal and of the low frequency reference signal by reading a predetermined number of super sectors located on a system track;

(c)(ii) determining an average value for the high frequency reference signal and the low frequency reference signal; and,

(c)(iii) determining the difference between the high frequency reference signal and the low frequency reference signal using the average values.

11. The method of claim 7, wherein the reading step (c) comprises:

(c)(i) taking multiple readings of the high frequency reference signal and of the low frequency reference signal by reading a single super sector a predetermined number of times;

(c)(ii) determining an average value for the high frequency reference signal and the low frequency reference signal; and,

(c)(iii) using the average values to determine the difference between the high frequency reference signal and the low frequency reference signal

12. The method of claim 7, wherein the value of the threshold level is adjusted for the radial location of the system track.

13. An apparatus for increasing the amount of data that can reliably be stored on a magnetic media comprising:

a read/write head for writing different frequency signals to and reading different frequency signals from the magnetic media; and

means for refreshing the magnetic media's data if a difference in decay rates between the different frequency signals exceeds a threshold value.

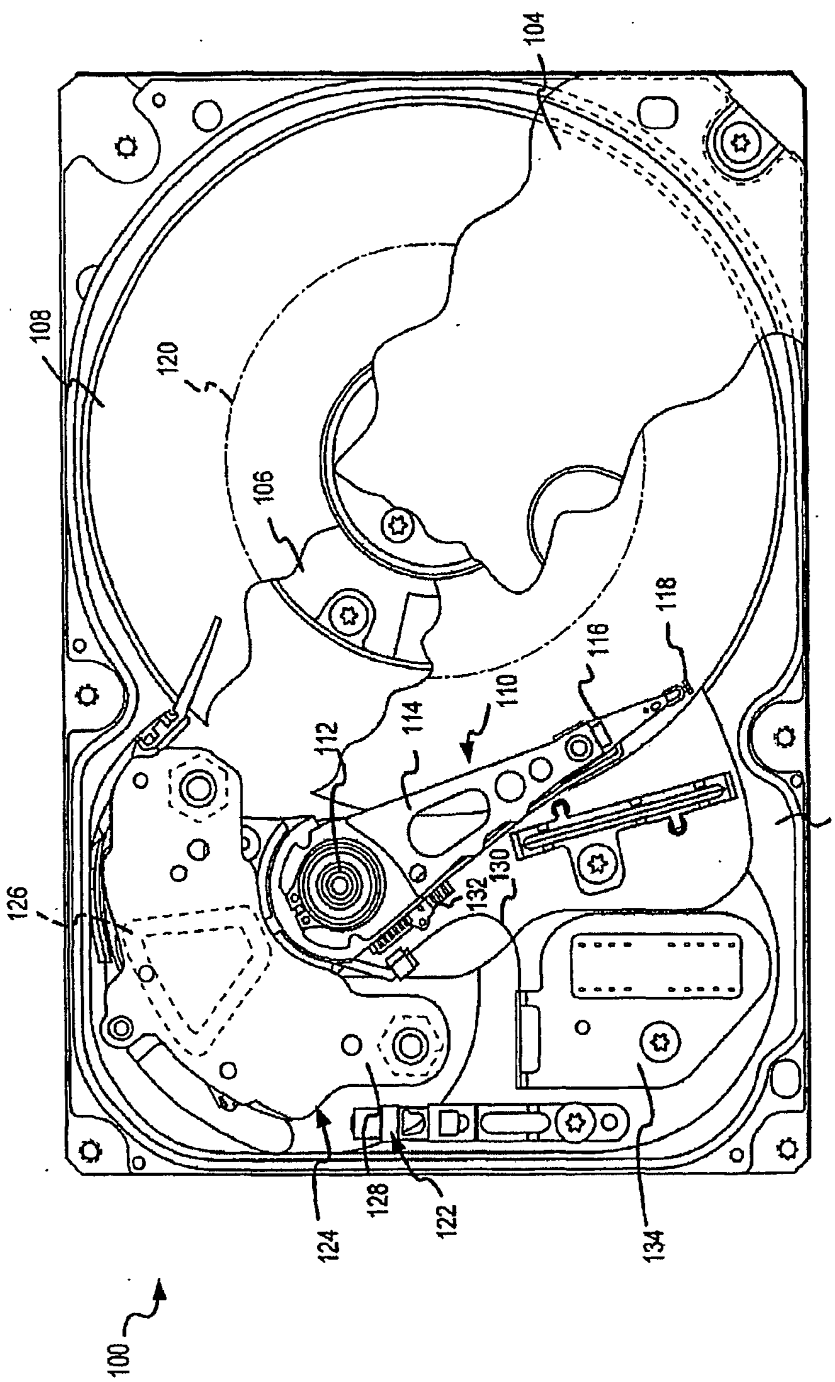
104
108
120
106
118
116
110
114
112
102
126
132
130
124
128
122
134
100

FIG.1

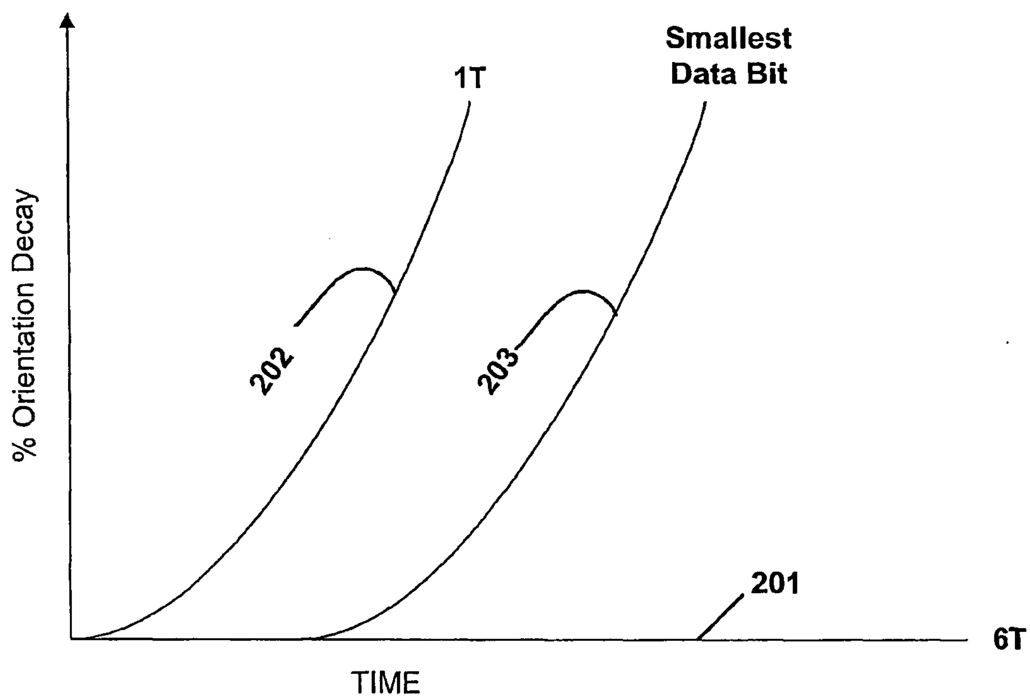

FIG. 2

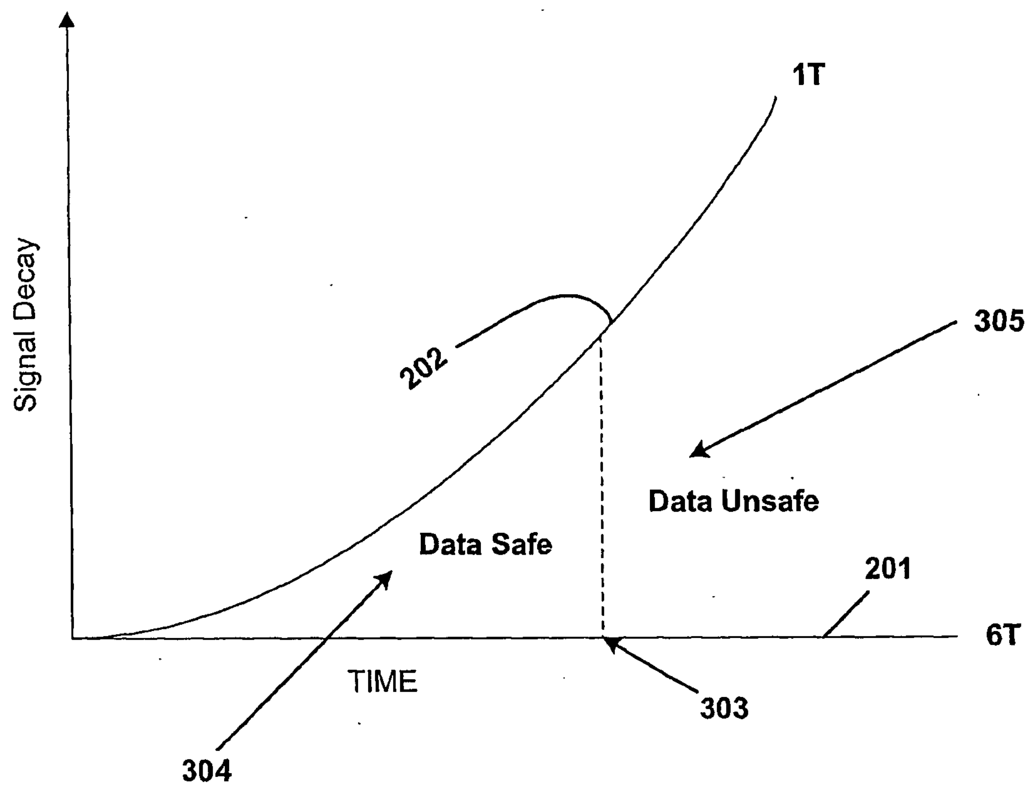
1T
Signal Decay
202
305
Data Unsafe
Data Safe
201
6T
TIME
303
304

FIG. 3

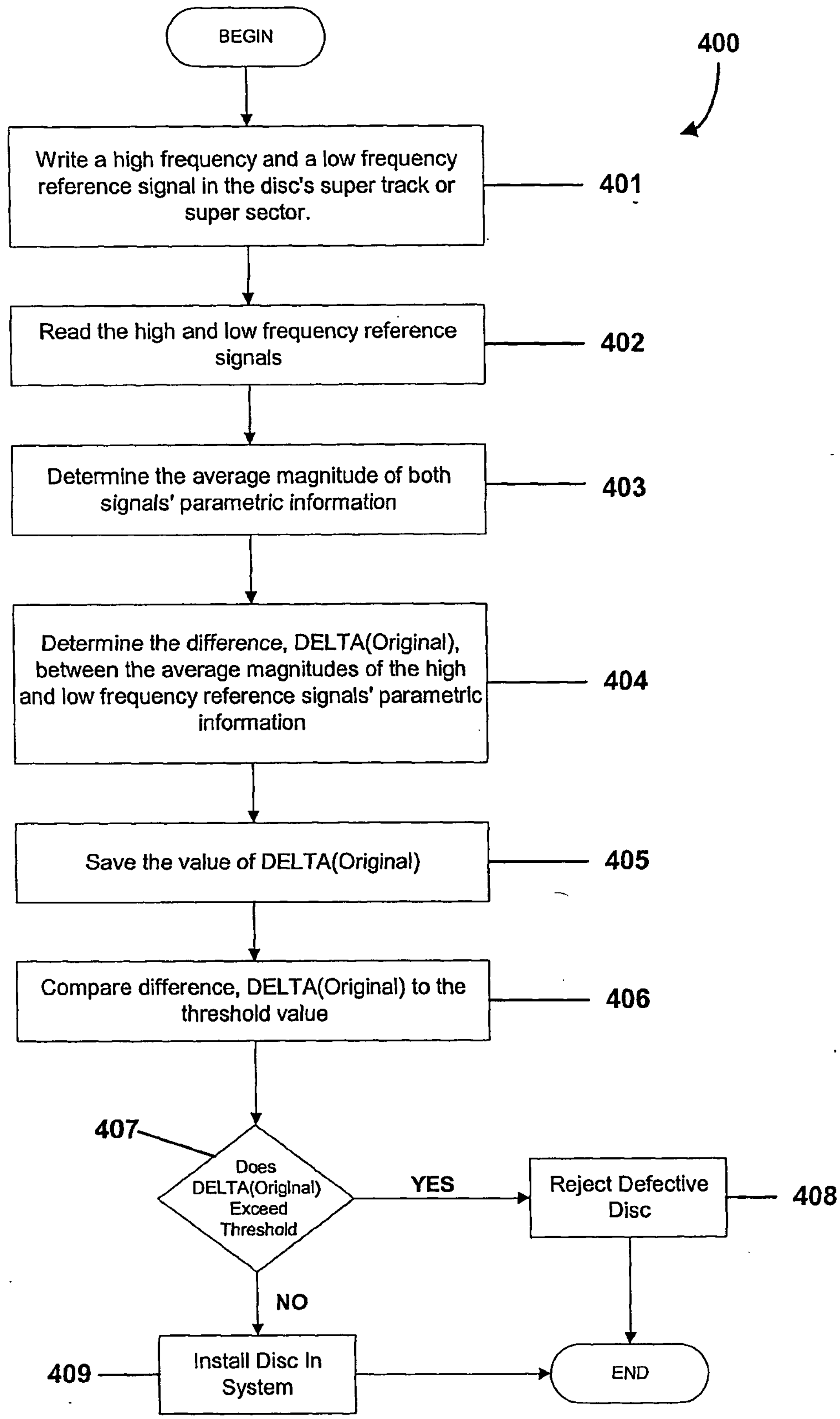
BEGIN
400
Write a high frequency and a low frequency reference signal in the disc's super track or super sector.
401
Read the high and low frequency reference signals
402
Determine the average magnitude of both signals' parametric information
403
Determine the difference, DELTA(Original), between the average magnitudes of the high and low frequency reference signals' parametric information
404
Save the value of DELTA(Original)
405
Compare difference, DELTA(Original) to the threshold value
406
407
Does DELTA(Original) Exceed Threshold
YES
Reject Defective Disc
408
NO
409
Install Disc In System
END

FIG. 4

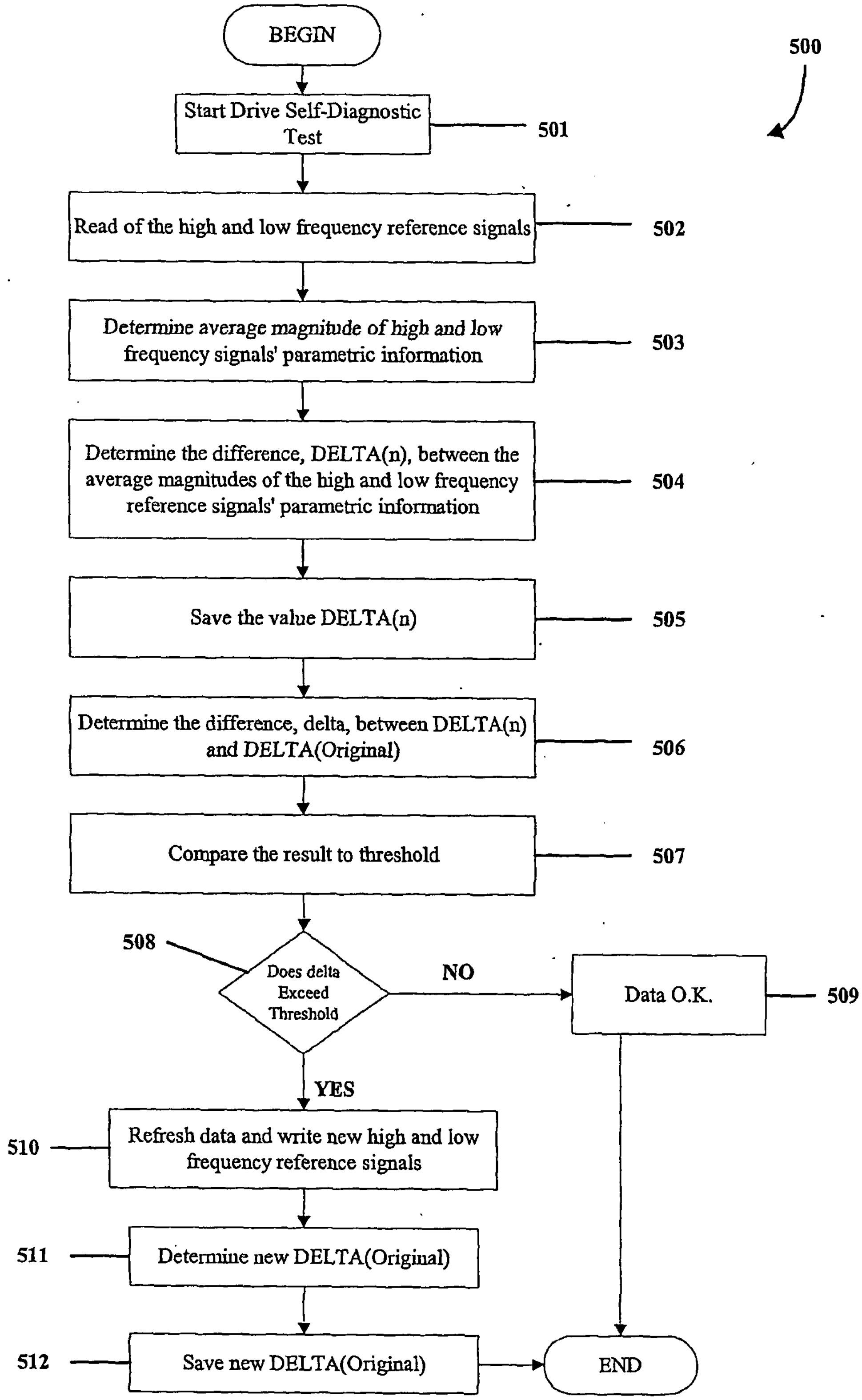
500
BEGIN
Start Drive Self-Diagnostic Test
501
Read of the high and low frequency reference signals
502
Determine average magnitude of high and low frequency signals' parametric information
503
Determine the difference, DELTA(n), between the average magnitudes of the high and low frequency reference signals' parametric information
504
Save the value DELTA(n)
505
Determine the difference, delta, between DELTA(n) and DELTA(Original)
506
Compare the result to threshold
507
508
Does delta Exceed Threshold
NO
Data O.K.
509
YES
510
Refresh data and write new high and low frequency reference signals
511
Determine new DELTA(Original)
512
Save new DELTA(Original)
END

FIG. 5

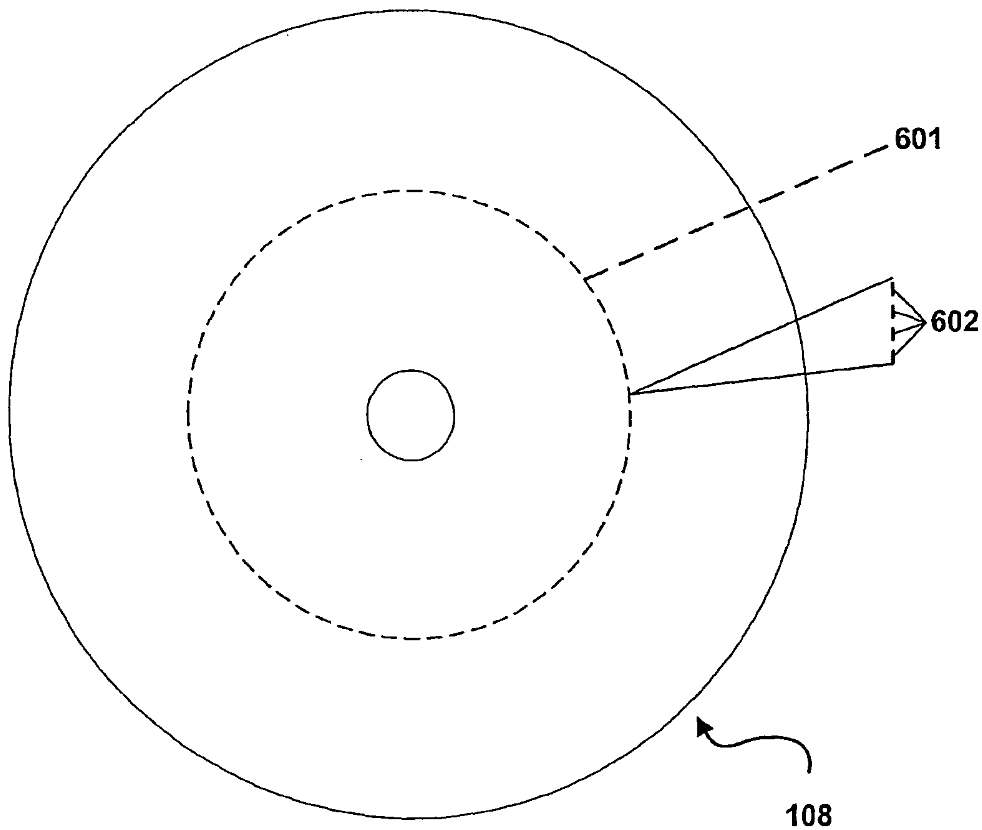

FIG. 6(a)

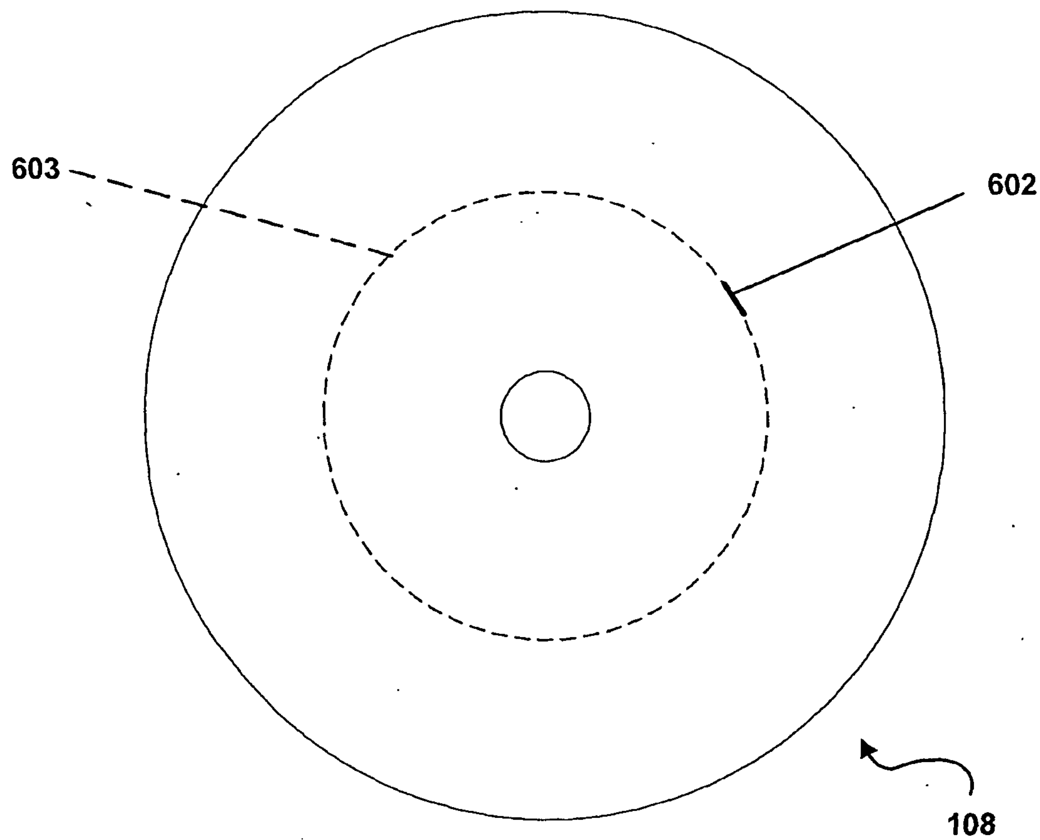

FIG. 6(b)

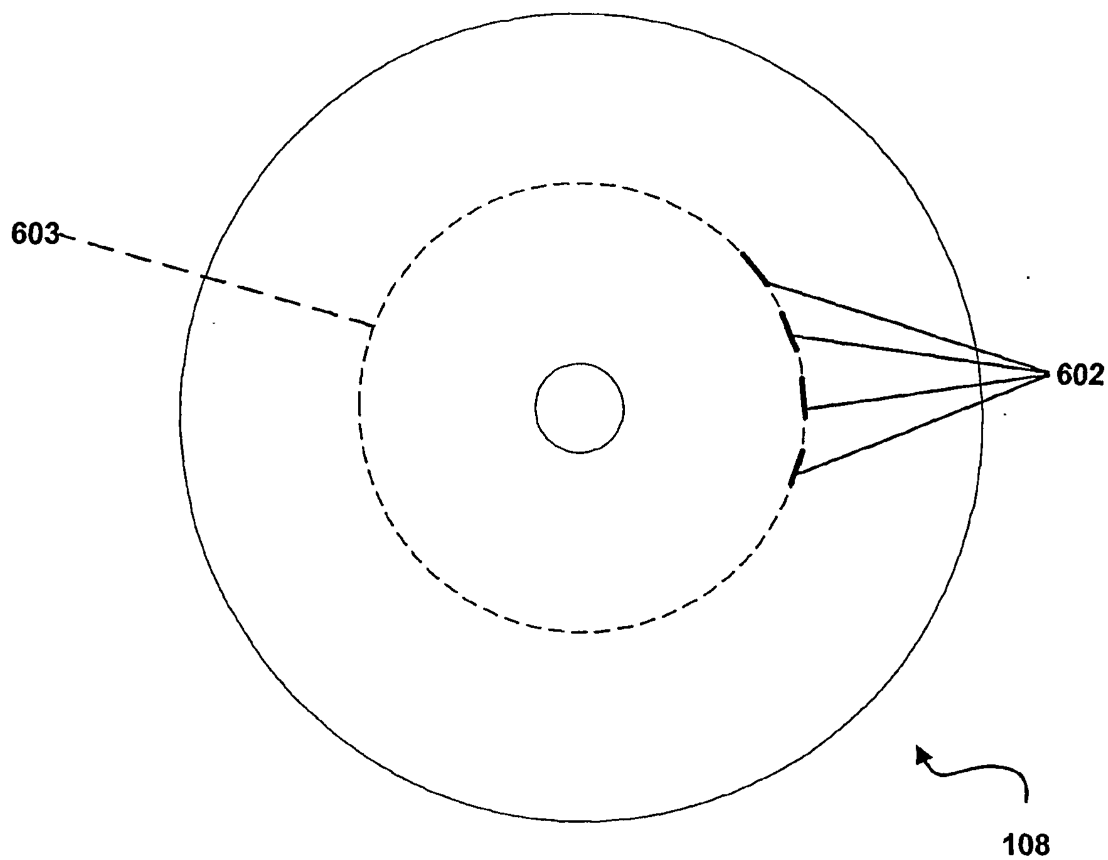

FIG. 6(c)